Testing ILC Cryomodules

- With beam - 9mA, 2600 bunches, (3nC), 3MHz, 5Hz:
  - ***Demonstrate beam phase and energy stability at nominal current***
    - ***(including a test of beam based feedbacks).***
  - Operation of a nominal RF unit at nominal gradient
    - Determine the operational gradient margin
  - Determine the required power overhead under practical operating conditions,
  - measure dark current and xray emission
    - (to be used to determine precise radiation dose-rate vert test criteria)
  - check for heating from higher order modes
    - (Jacek – Next week at TTC 19 April)

DESY ILC 9mA test: Where are we with accomplishments on this list?

- Long-pulse high beam-loading (9mA) demonstration
  - 800μs pulse with 2400 bunches (3MHz) close to √
  - 3nC per bunch √
  - Beam energy 700 MeV ≤ E_{beam} ≤ 1 GeV √
- Primary goals
  - Demonstration of beam energy stability (ΔE/E < 0.1%). X
    - Over extended period X
  - Characterisation of energy stability limitations Partially done
    - Operations close to gradient limits X
  - Quantification of control overhead X
    - Minimum required klystron overhead for LLRF control X
  - HOM absorber studies (cryoload)
  - …

- It has been a major challenge for FLASH
  - Pushes many current operational limits

Gustavo Cancelo, Julien Branlard, Brian Chase

Secondary goals:

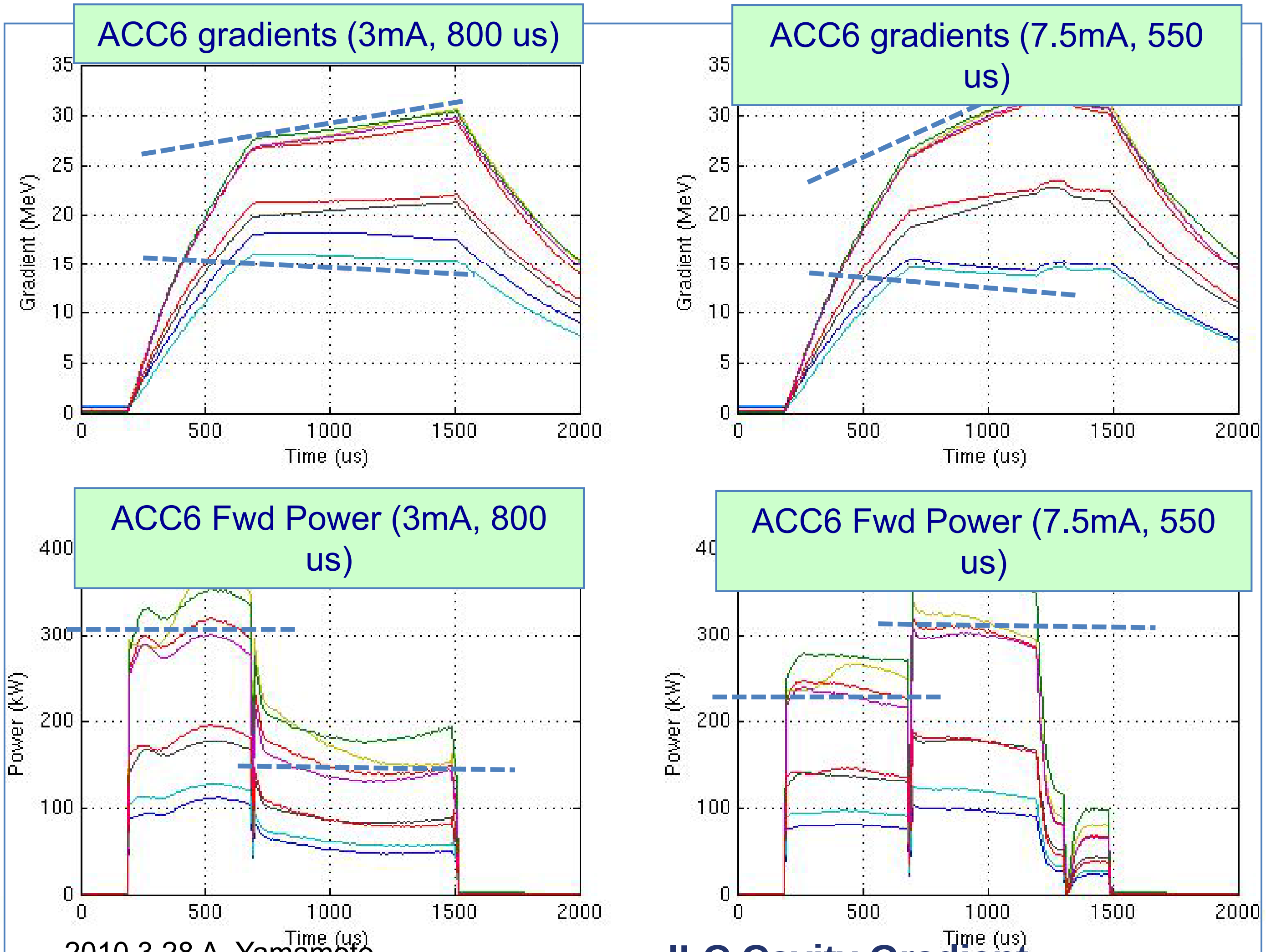
- to determine subsystem performance--
  - recovery procedures,
  - quench rates,
  - coupler breakdowns,
  - testing reliability,
  - practical issues.

FLASH / TTF tests - Sept 2009

- Gradient slopes
  - ***How to operate a CM with a large distribution of cavity limiting gradients?*** (Unintended)
    - 19 to 33 MV/m
  - How to optimize and stabilize cavity tuning and coupling (Q_ext)
- 'Vector Sum' control
  - Calibration -
  - --> the 'actual' vector sum, measured by energy spectrometer is not the same as the combined vector sum
  - Correction process will un-balance - and can drive quench

From Nick's talk at FLASH workshop at DESY, on Feb. 22:

Cavity tilts with long bunch trains and heavy beam loading (3mA and 7.5mA, long bunch trains)


ACC6 gradients (3mA, 800 us)

ACC6 gradients (7.5mA, 550 us)

ACC6 Fwd Power (3mA, 800 us)

ACC6 Fwd Power (7.5mA, 550 us)

Gradient tilts are a consequence of using a single RF source to power cavities running at different gradients

At 7.5mA, ACC6 cavities #1 and #2 approached their quench limits at the end of the pulse

The RF power during flat-top is higher than the fill power for the 7.5mA case setup from 08/24/2009

ACC4	**21.8** MV/m			**181**	MeV		Max	191	Mev	Δ	10
Pin, MW	**1.51**		RF power	OK							
Qext	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0			
A, dB	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	*not measured*		
A (klystron)	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1			
Pcav, kW	169.7	169.7	169.7	169.7	169.7	169.7	169.7	169.7		1357.9	155
Ecav, MV/m	21.85	21.85	21.85	21.85	21.85	21.85	21.85	21.85		21.8	MV/m
I match	7.30	7.30	7.30	7.30	7.30	7.30	7.30	7.30			
Ecav, max	23	23	23	23	23	23	23	23		23.0	
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*			
Δφ	*not measured*									*beam - forward RF*	

ACC4 cavities have motorized 3-stub

ACC5	**22.6** MV/m			**187**	MeV		Max	231	Mev	Δ	44
Pin, MW	**1.61**		RF power	OK							
Qext	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0			
A, dB	9.67	9.64	9.61	9.53	9.34	9.35	9.38	9.39	*measured*		
A (klystron)	14.87	14.84	14.81	14.73	14.54	14.55	14.58	14.59			
Pcav, kW	173.5	174.7	175.9	179.2	187.2	186.8	185.5	185.1		1447.8	160
Ecav, MV/m	22.09	22.17	22.24	22.45	22.95	22.92	22.84	22.81		22.6	MV/m
I match	7.38	7.40	7.43	7.50	7.66	7.65	7.63	7.62			
Ecav, max	29	27	28	28	29	28	28	26		27.9	
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*			
Δφ	0	-6	11	1	15	6	6	20		*beam - forward RF*	

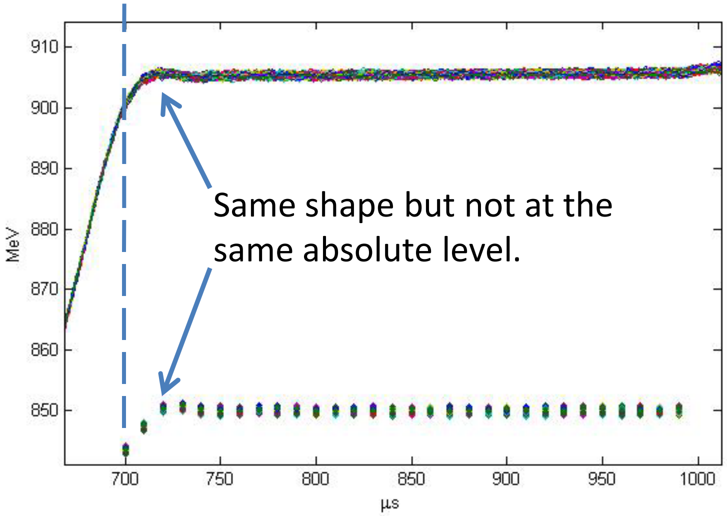
ACC5 cavities have motorized 3-stub tuners

ACC6	**26.5** MV/m			**220**	MeV		Max	238	Mev	Δ	18	
Pin, MW	**2.18**		RF power	OK								
Qext	2.95	2.97	3.00	2.98	3.00	2.98	2.99	2.98	11/21/2007			
A, dB	7.85	7.54	8.16	8.31	12.27	12.03	10.28	10.37	*measured*			
A, (klystron)	11.65	11.34	11.96	12.11	16.07	15.83	14.08	14.17				
Pcav, kW	357.6	384.0	332.9	321.6	129.2	136.6	204.3	200.2		2066.5	113	
Ecav, MV/m	31.82	32.93	30.60	30.12	19.06	19.62	23.99	23.76		26.5	MV/m	
I match	10.81	11.11	10.22	10.13	6.37	6.60	8.04	7.99				8.91
Ecav, max	34	32	34	32	21	21	29	26		28.6		
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*				
Δφ	0	0	0	0	0	0	0	0		*beam - forward RF*		

ACC6 cavities have motorized couplers and phase shifters

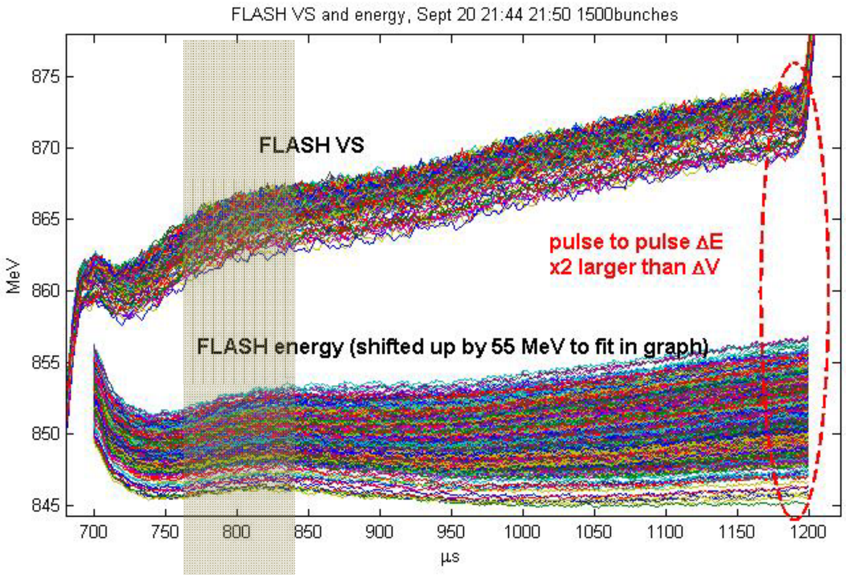
Energy stability

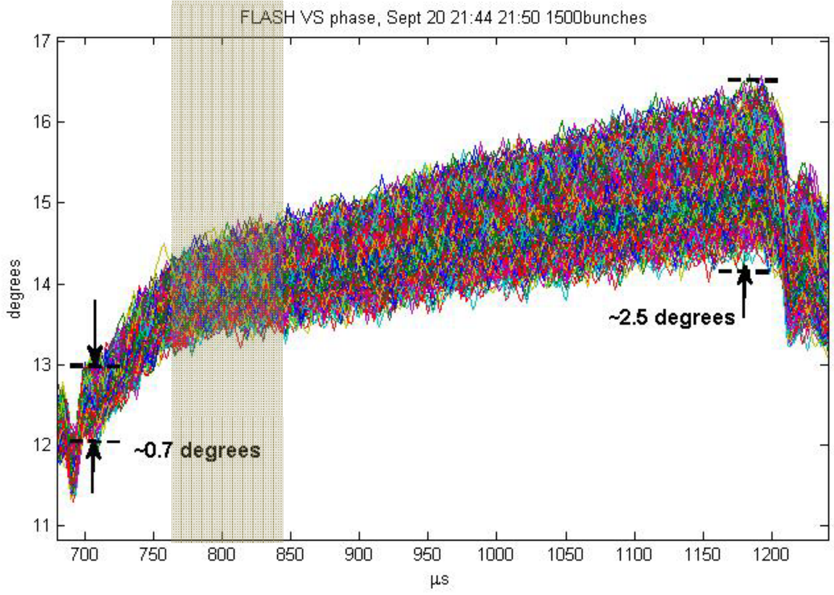
Sept. 13 18:40 18:45, 3mA?, 30 bunches



Same shape but not at the same absolute level.

Sept. 20 21:44 21:50 1500bunches





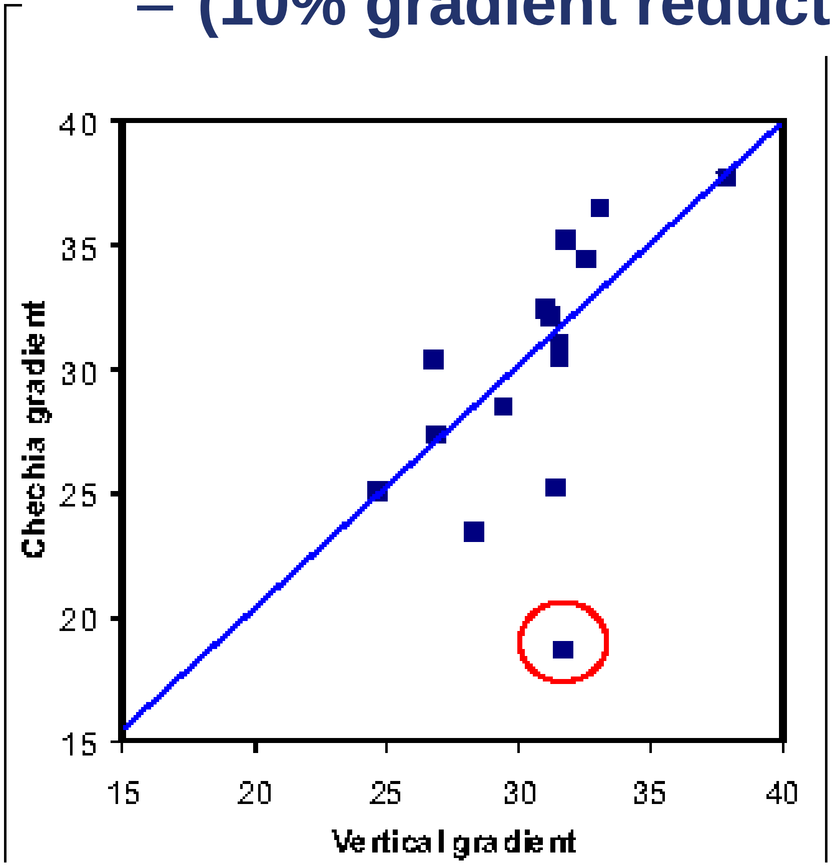
- Energy and VS disturbances
  - Intra pulse
    - Unstable VS field at beam injection (i.e. flattop not completely flat).
    - VS amplitude not flat (~12 MV change in 500µs).
    - Phase not flat (~4 degree change in 500µs).
    - VS ampl./phase flatness depend on day and time.
  - Pulse to pulse
    - ~1% peak to peak ΔE/E, non uniform along flattop.
    - Phase Δφ/φ non uniform along flattop.

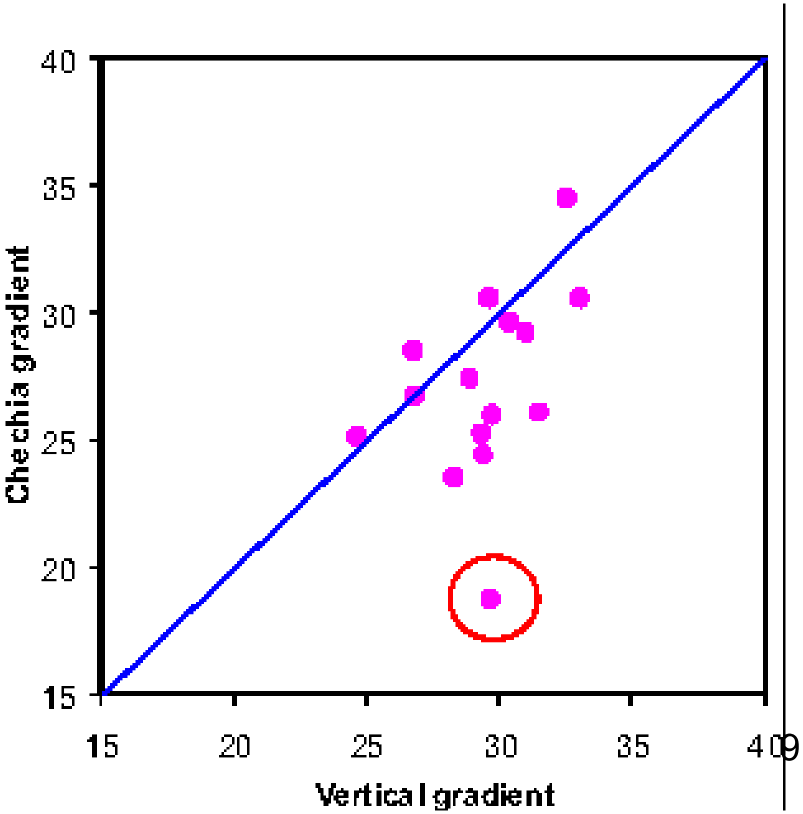
To measure 'cavity availability' at a given ' operational margin':

- simple experimental approach. (operational margin, cavity availability, etc)
- Measure cavity trip or quench rate as a function of gradient as the gradient is raised closer and closer to the expected performance limit - without beam.
  - one day we have 5*3600*24 = 4e5 pulses,
    - decent performance should be claimed if no single faulted pulse is observed in the 24 hour day.
  - Should flatten the pulse and control the Lorentz Force Detuning (LFD)→ no missed pulses up to 0.99 of expected limit.
  - Start one cavity at a time (HTS?)
  - more interesting with field emitting cavities and groups of cavities where the distribution system has been tailored specifically to match the limits
- Success here shows the effectiveness of LFD and RF amplitude controls.

Cavity performance limits – assembly and test:

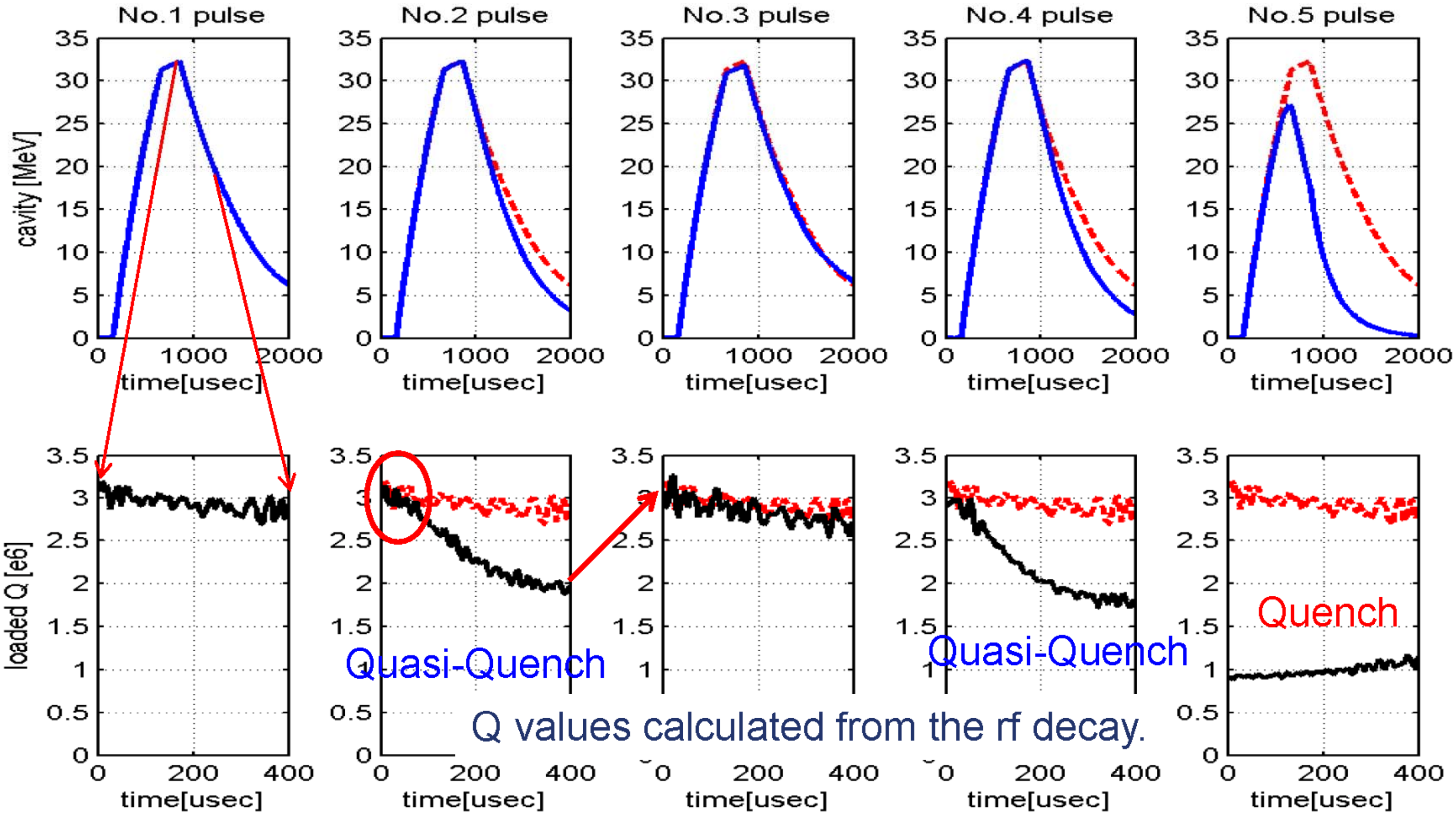
- Horizontal vs. Vertical Test (8% reduction):
  - **Presumably similar changes H vs CM**
- ILC gradient cost leverage ~1/2
  - **(10% gradient reduction increases cost 5%)**





Reschke et al SRF2007

Quasi-quench



Quasi-Quench

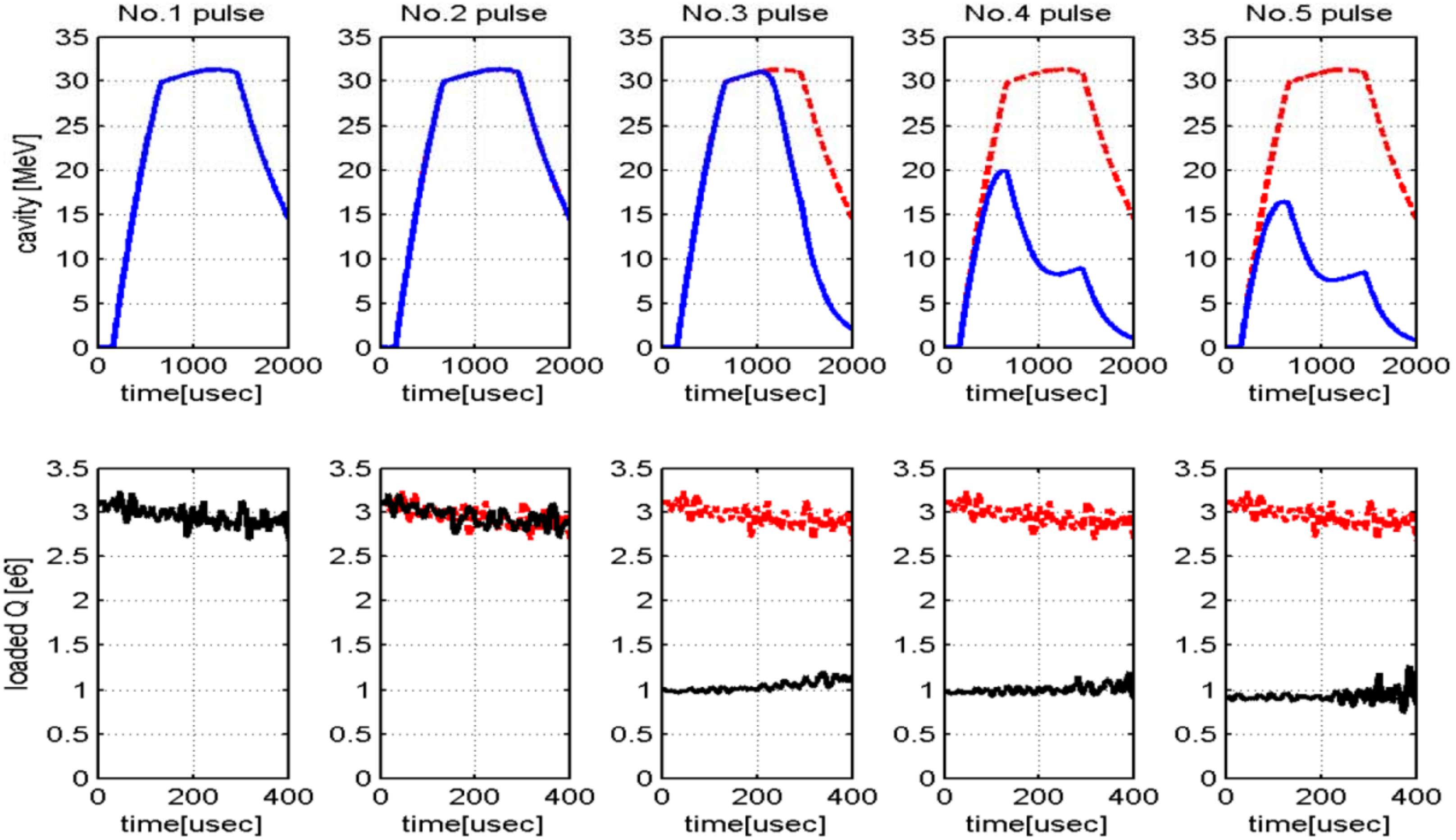
Quasi-Quench

Quench

Q values calculated from the rf decay.

- In case of the shorter flattop (~200 us or less), “quasi-quench” took place.
- At “Quasi-quench”, loaded Q decreases from normal value (~3e6) to 2e6.
- Sometimes recovery at next pulse was observed..

Quench behavior at long pulse



- At longer pulse (~800 us flattop), no “quasi-quench” was observed.
- Once quench took place, no recovery was observed probably due to the larger energy dose to quenched area.

Power and Gradient Margins

- What are the practical performance limits?
  - **which aspects dominate and what effort is required to improve them? *What is the dependence on 'software'?* (TOYOTA)**
- the ***cavity field*** may exceed limiting field in a given cavity
  - **Criticality: quench or performance degraded ←not LHC!**
  - **Recovery 'cost'.**
- the ***HLRF system*** does not provide the optimum field.
  - **Reconfiguration cost.**
- external constraints:
  - ***Radiation, cryogenics*** **or cavity auxiliary equipment (*coupler, tuner, instrumentation*…)**

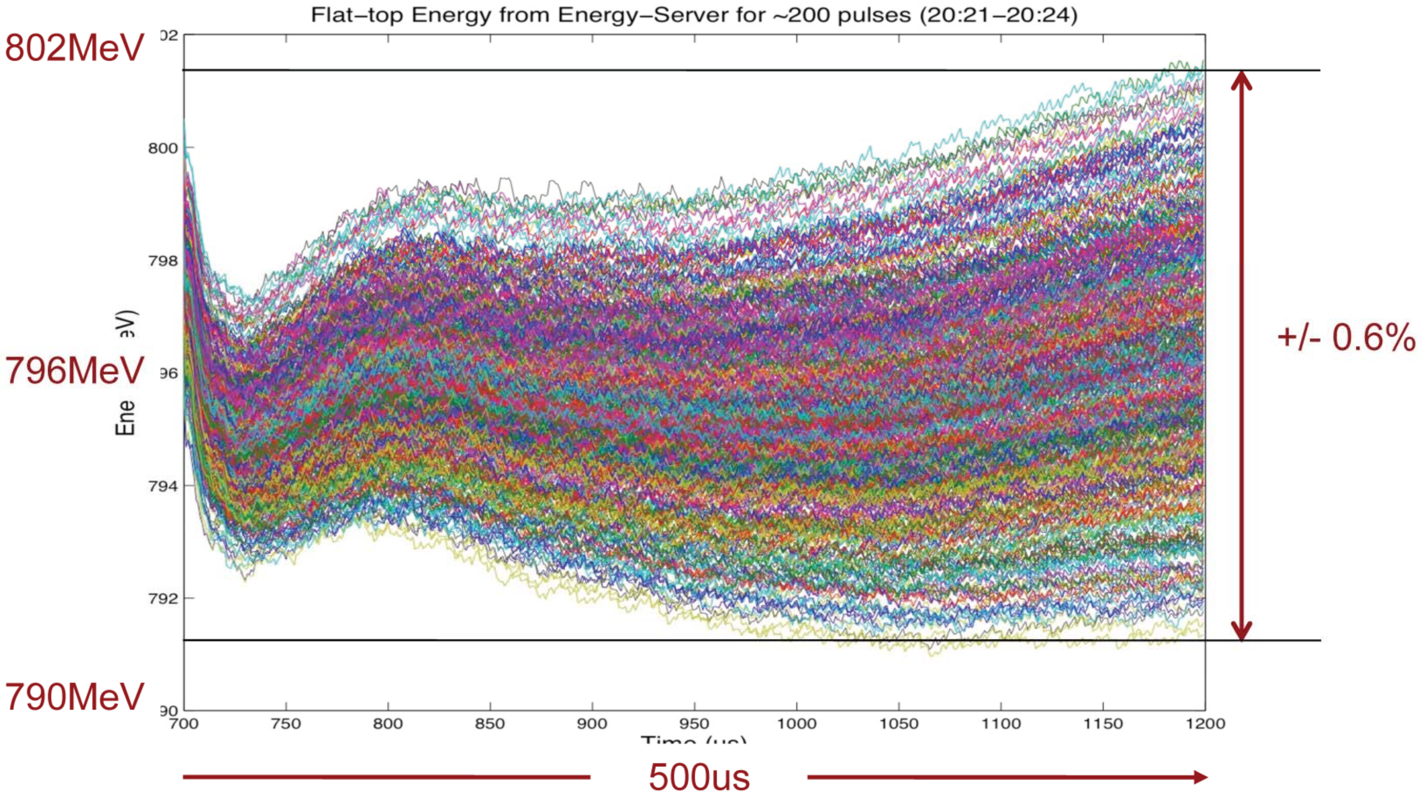
Find the ‘margin’ with beam:

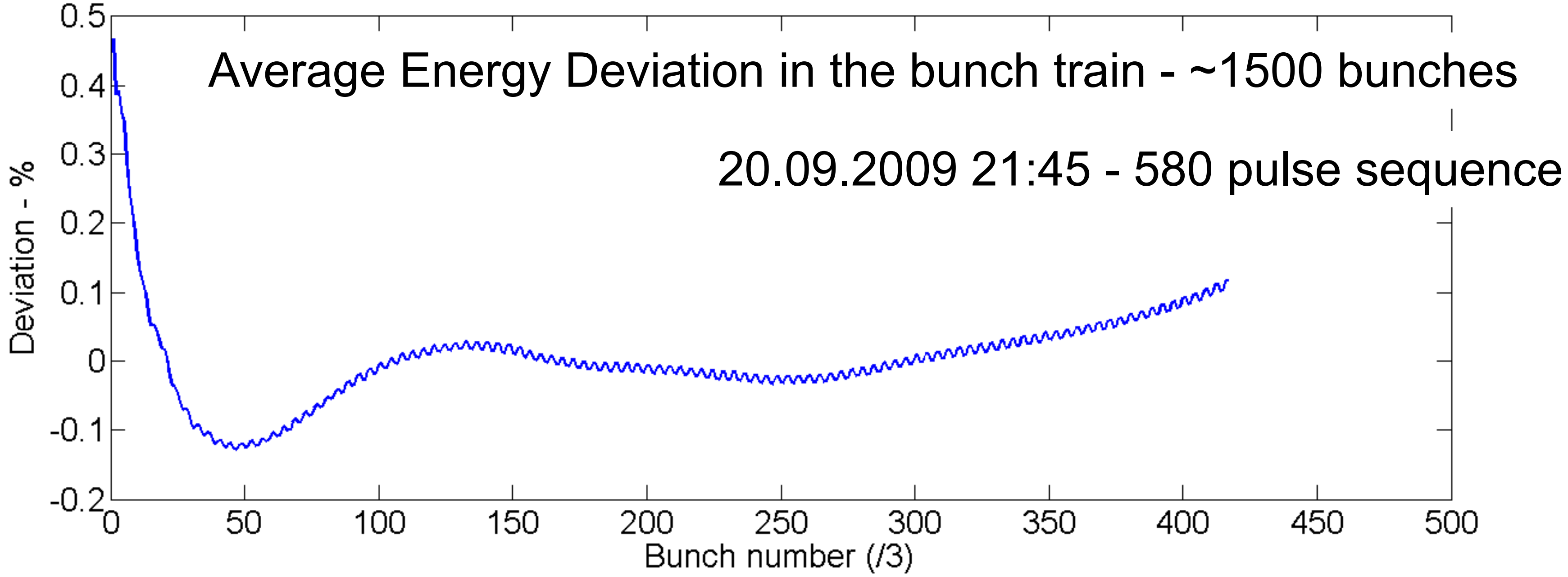
- Raise the current and repeat trip rate measurement.
  - (idealized, but is easy to understand)
- define the operational gradient as that level (% of expected limits) which can be indefinitely maintained at nominal beam current.
- Suggestion: No trips in one day, for a given cavity, at 3% reduced voltage (and full beam intensity.)
- Success here shows functional disturbance response control and an integrated (including beam loading) regulation controller.

Specifics (observed at DESY):

- (fixes needed at Flash – Suggestions)
- 1) RF vector sum calibration,
- 2) coupler mechanism adjust-ability.
  - Must be able to use set-restore for this system in order to flatten the RF as needed,
- 3) transient control and beam loading amplitude dependent control.

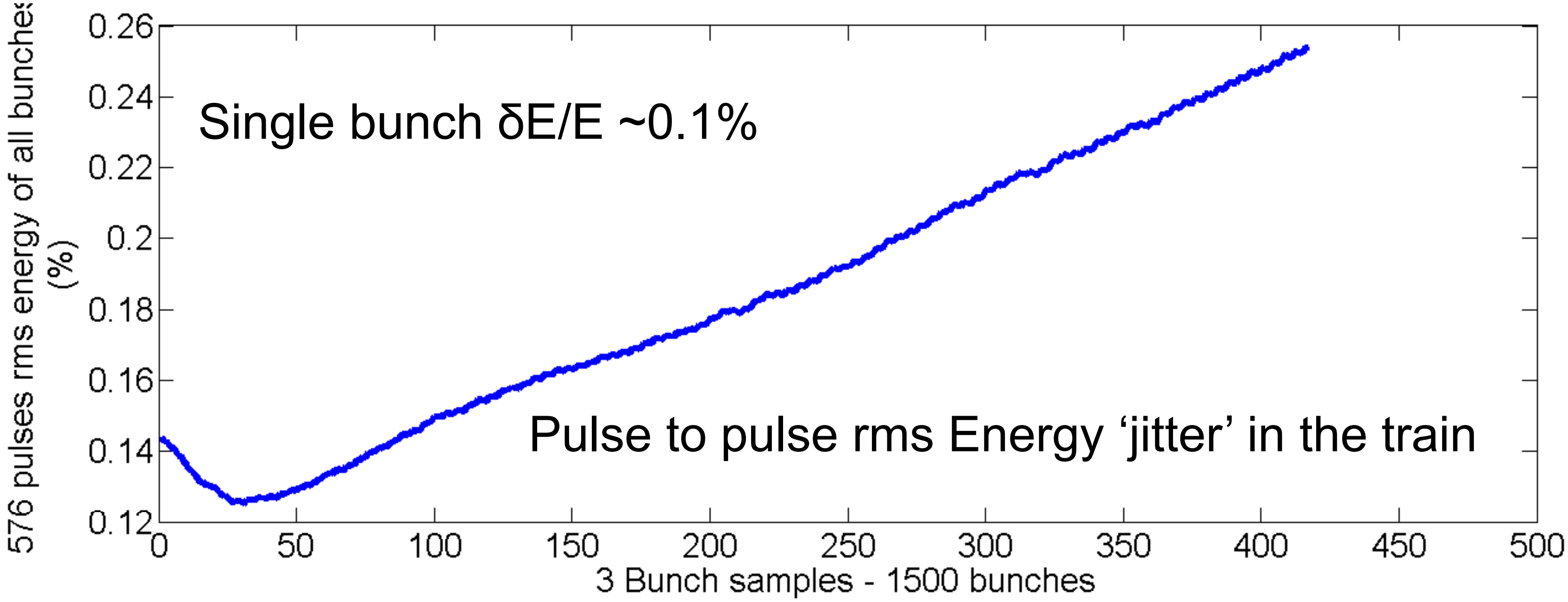
Example of pulse-to-pulse energy jitter (500us, ~3mA, 200 pulses overlaid)





Average Energy Deviation in the bunch train - ~1500 bunches

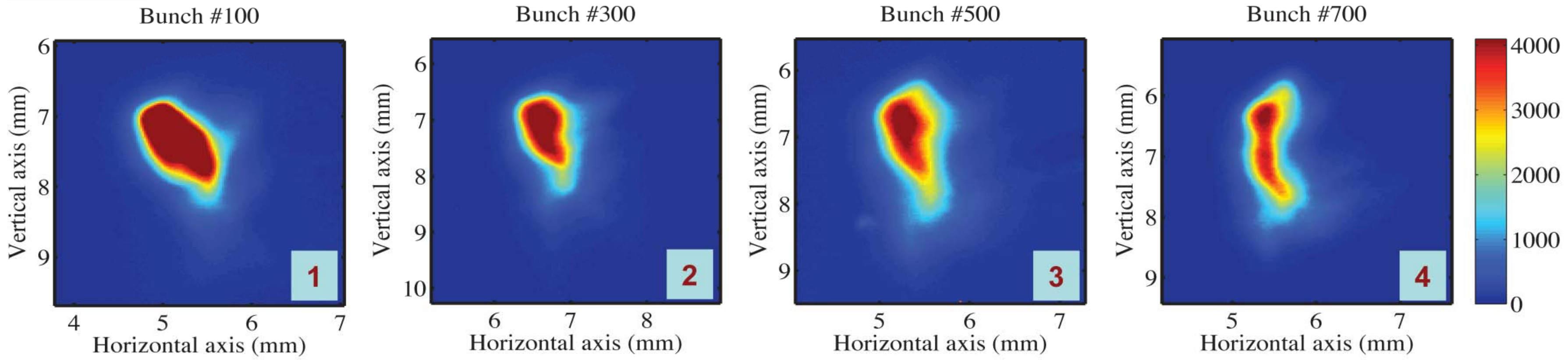
20.09.2009 21:45 - 580 pulse sequence

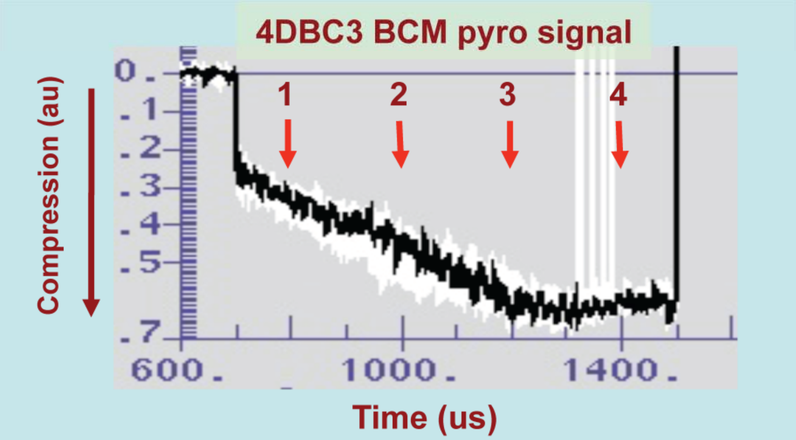


Single bunch δE/E ~0.1%

Pulse to pulse rms Energy ‘jitter’ in the train

Transverse bunch distributions along bunch-train (800 bunches @ 1MHz, ~3nC/bunch)





First bunch at 700us, last bunch at 1500us

- Transverse bunch distributions clearly show changes in bunch size and shape over the long bunch train
- ACC1 phase and BCM signals appear correlated with the changes in bunch distributions
- **LOLA was only available diagnostic for single-bunch measurements with long bunch trains at full-energy**

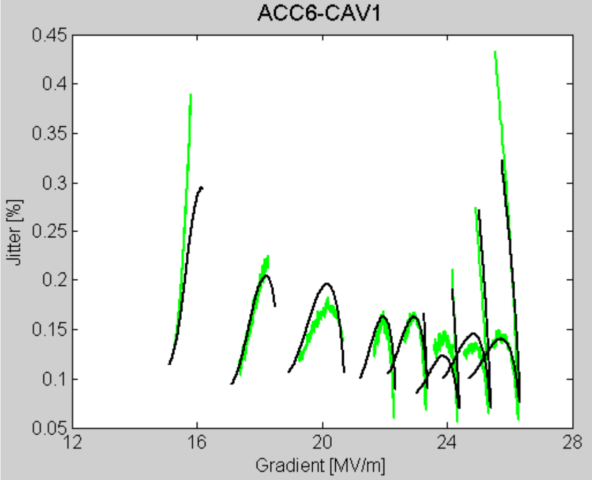
Compressor monitors missing: (phase/E)

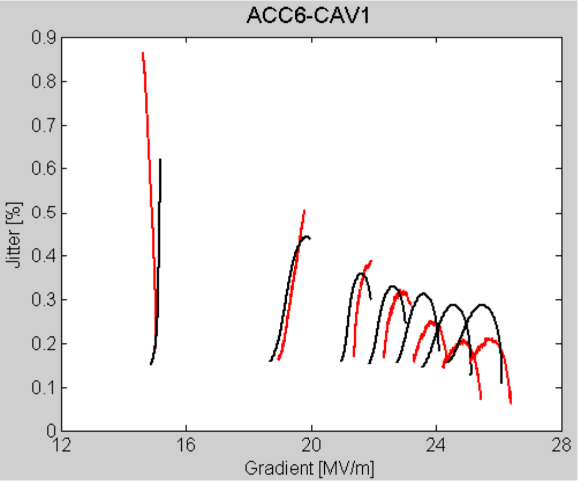
Cavity Gradient Stability

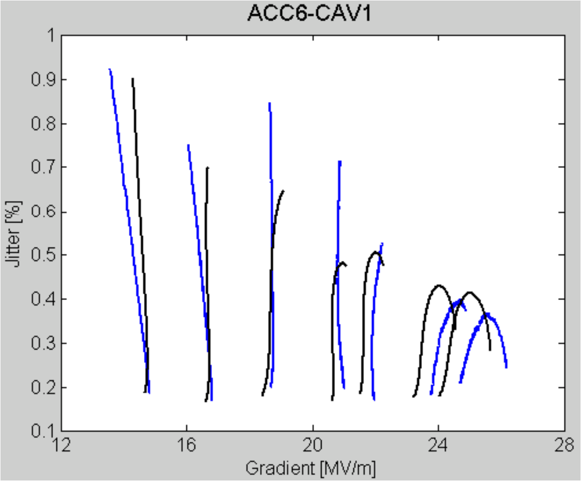
January 2009 Measurement

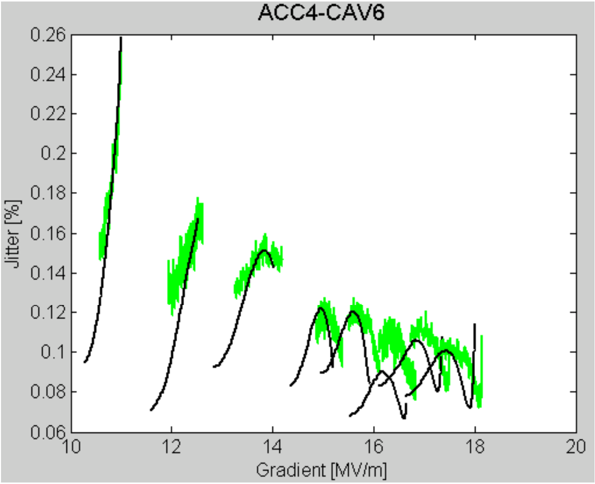
Beam and feedback off

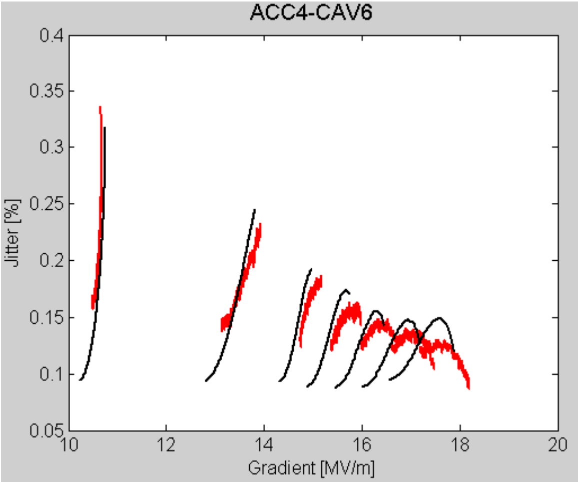
Comparison of beam-off measurements of pulse-to-pulse cavity gradient jitter during the flattop period for different gradients and initial cavity detuning (green, red and blue lines) to a cavity fill model including Lorentz force detuning (black lines) with two degrees of freedom (initial and initial rms detuning)

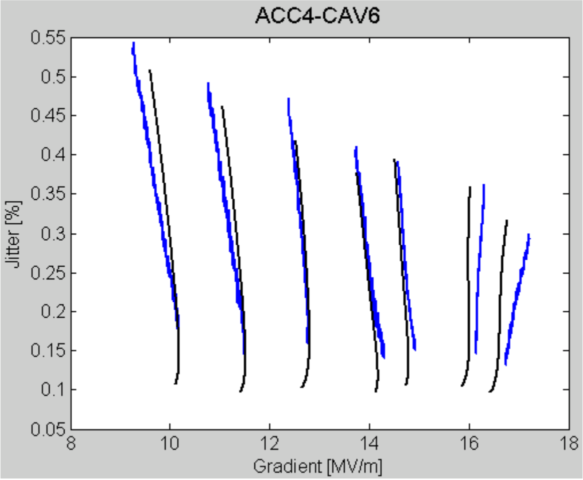






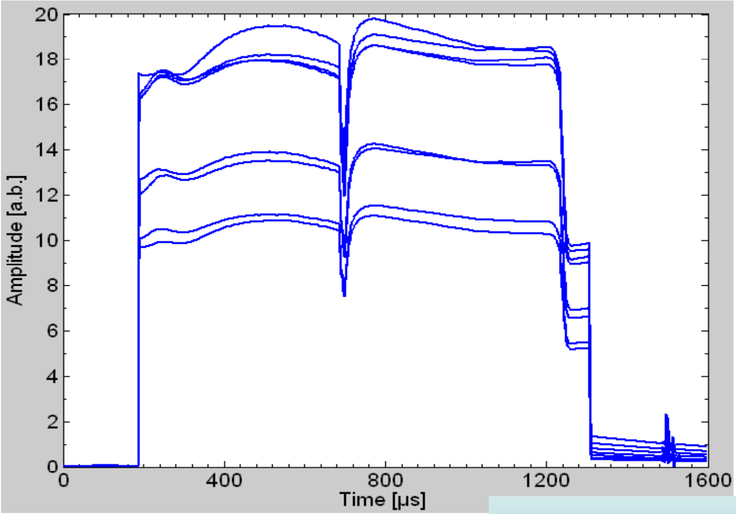


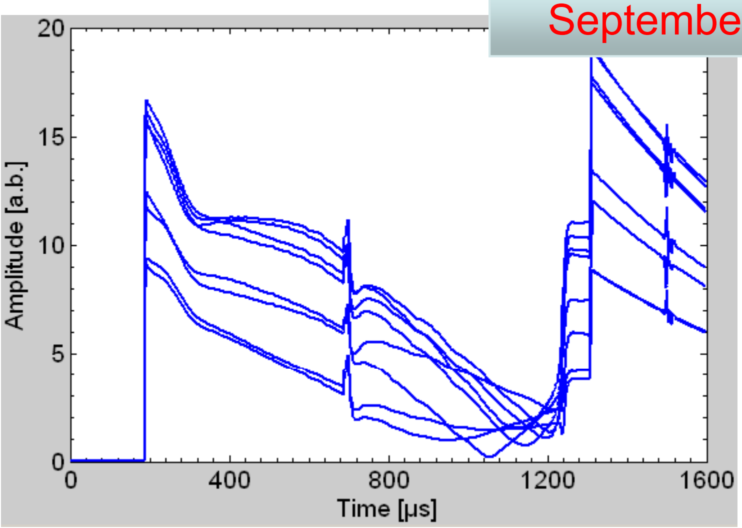




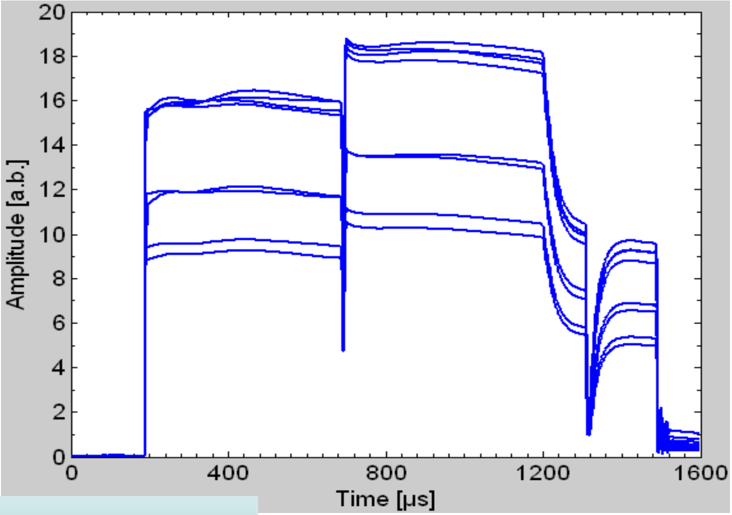
Forward and Reflected Signal with Beam On

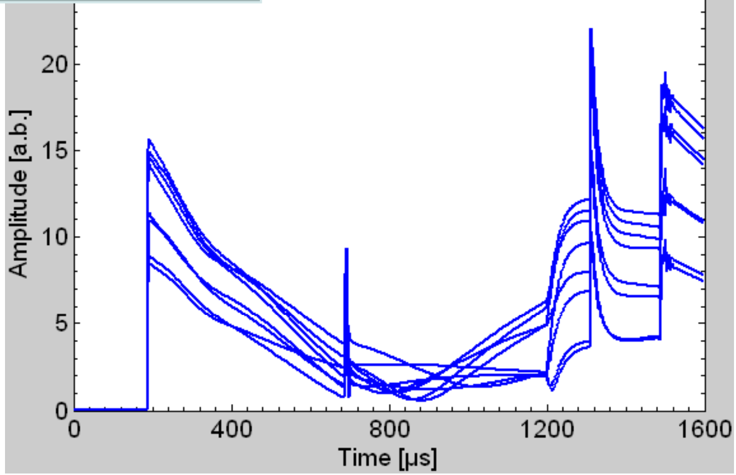
Cavities in ACC6 with piezo off
3MHz/3nC beam with 1600 bunches





Cavities in ACC6 with Piezo on
3MHz/3nC beam with 1500 bunches





September 2009 Measurement

Suggested Studies

- Produce ILC-spec beam
- Estimate required operational overheads:
  - **Gradient**
  - **HLRF Power**
- Evaluate sub-system performance
  - **Cryogenic**
  - **HLRF power distribution: Coupler / waveguide components**
- Dark Current and Ambient radiation

How to control and optimize operation near the limits:

With full power beam and support systems optimized, Test:

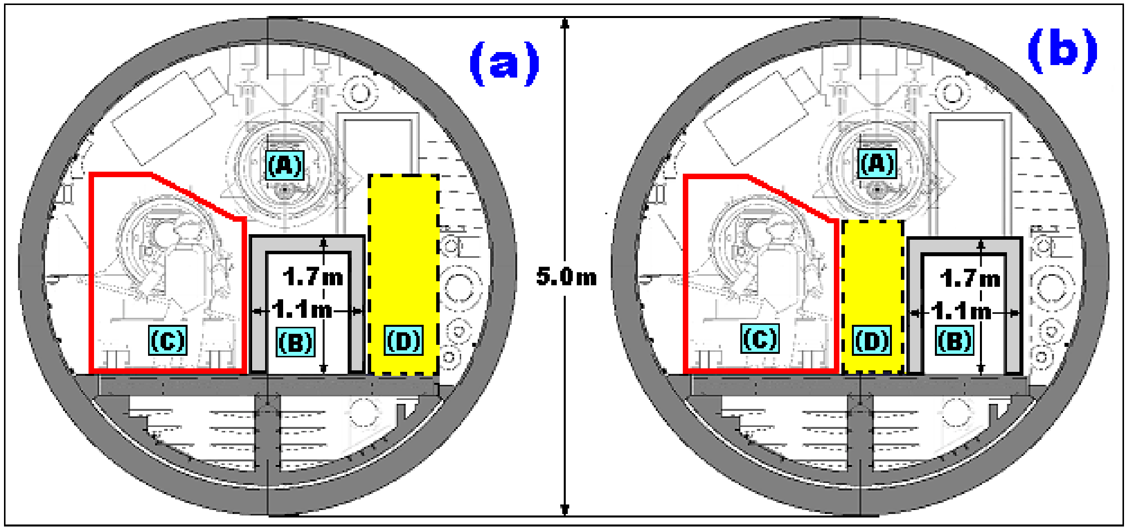
- ***Controls:***
  - **create artificial limits which lie below the real ones and probe ability to conform to these during real operation. Voltage, coupler, radiation, other - thermal.**
- ***Thresholds***:
  - **Couple this with tests and cataloging real limits**
- ***Response***:
  - **For many tests: *Don't respond, just log it*.**
  - **But eventually the response becomes part of the performance measure. For example: quench recovery.**
- ***System***:
  - **Ultimate 'stress test'… may not be practical at FLASH (user facility)**

Cryogenics and HLRF

- XFEL TDR/SNS Cryogenic and HLRF ‘overhead’
  - **(e.g. cryo overhead: 50%)**
- ILC HLRF overhead much less →
  - **Is it enough?**
- Suggested Study:
  - ***Artificially reduce HLRF margin*** **by reducing HV or through introduction of an artificial transfer function**
  - **Measure full power performance degradation resulting from reduced controls leverage**

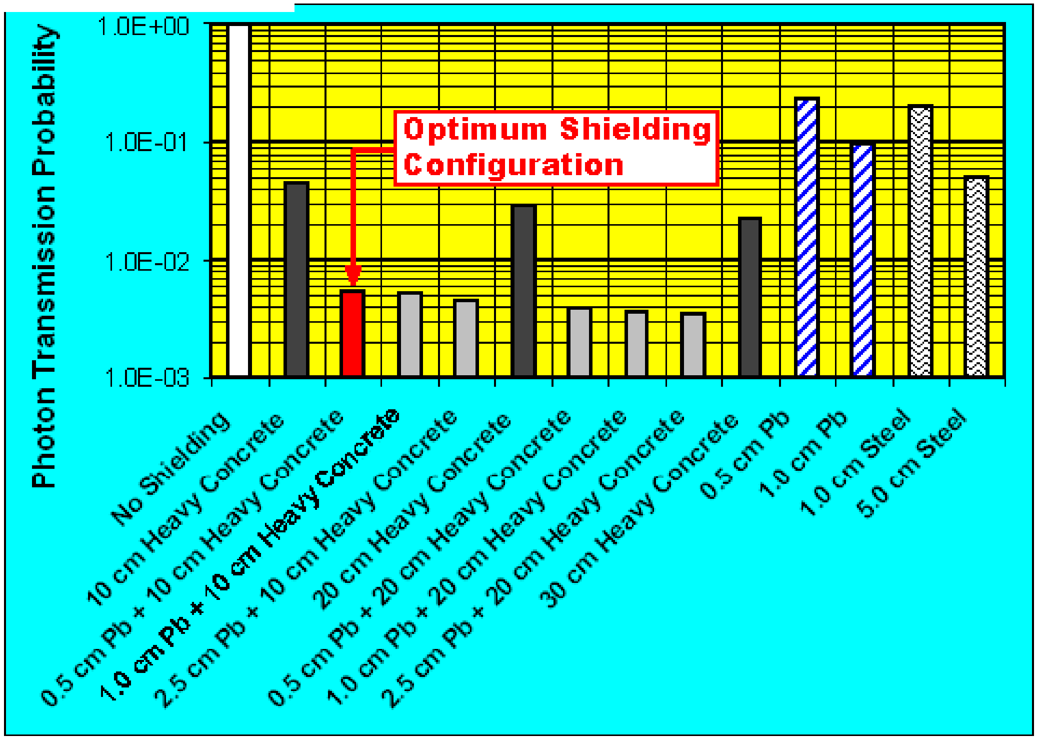
Radiation

- Dark Current Example: (See also SNS)
  - **A few uA from a given cavity, captured in a 38 m ILC RF Unit (between 2 focusing magnets):**
  - **Energy range: few MeV to ~26*35 MeV**
    - 0.1 W to 20 W / 38 m (for one 5uA emitter)
    - Cryo load limit ~ 1 W/m
  - **(FLASH dominated by RF gun emission)**
  - **LHC: 0.02 W/m at nominal 7 TeV ops**
- Electronics is sensitive to:
  - ***beam power (damage)* and**
  - **neutrons ('Single Event Upset') ← follow LHC**
- (Residual activation 100x worse per watt in proton machine – two environments otherwise similar)
- *Electronics Radiation Damage from CM Dark Current is a critical study topic*



Impact of Radiation shielding on single tunnel

- XFEL Scheme
- LHC Scheme – next:

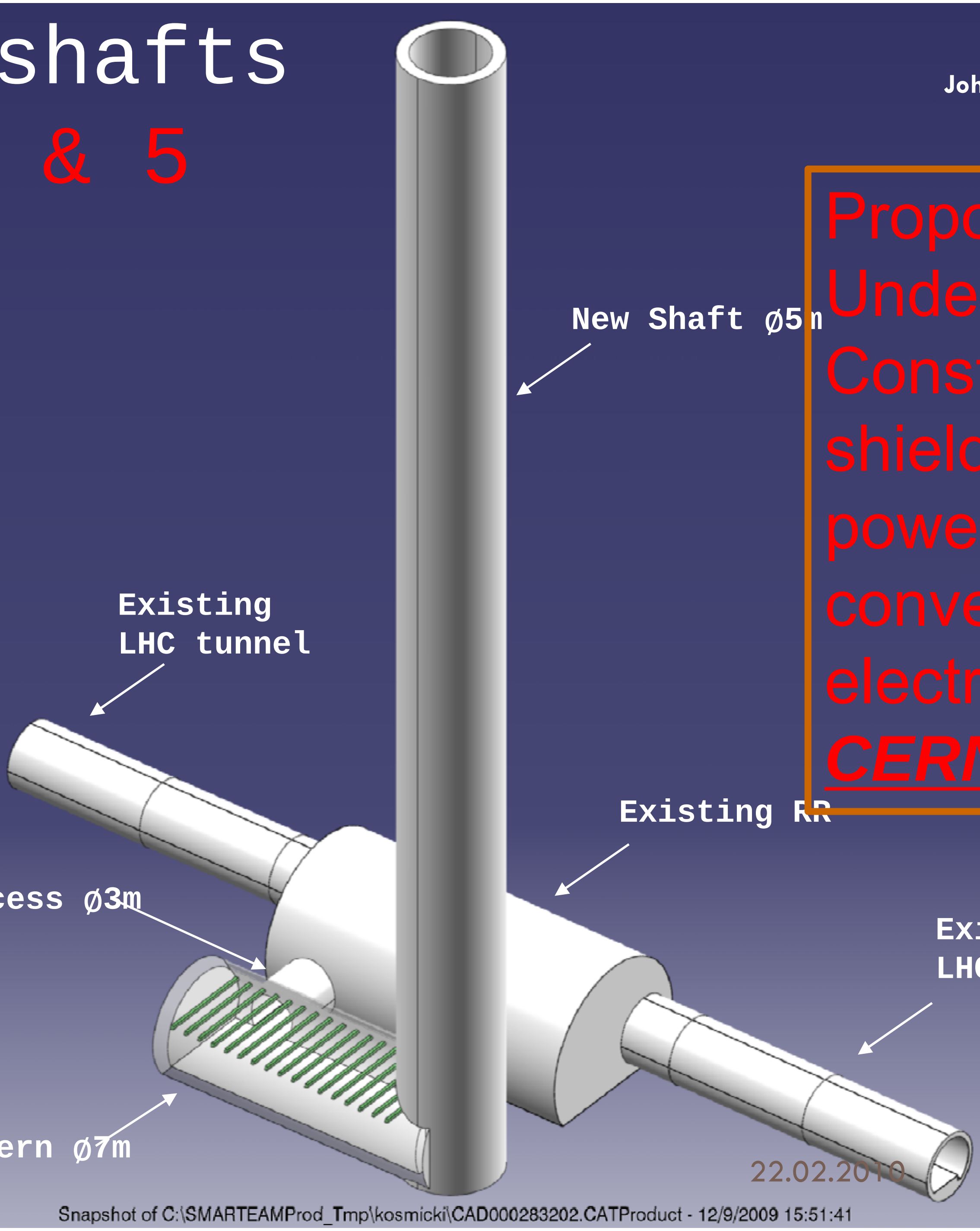


RR's + shafts

Point 1 & 5

John Osborne GS-SEM

Proposed Underground Construction to shield LHC power converter electronics: ***CERN***

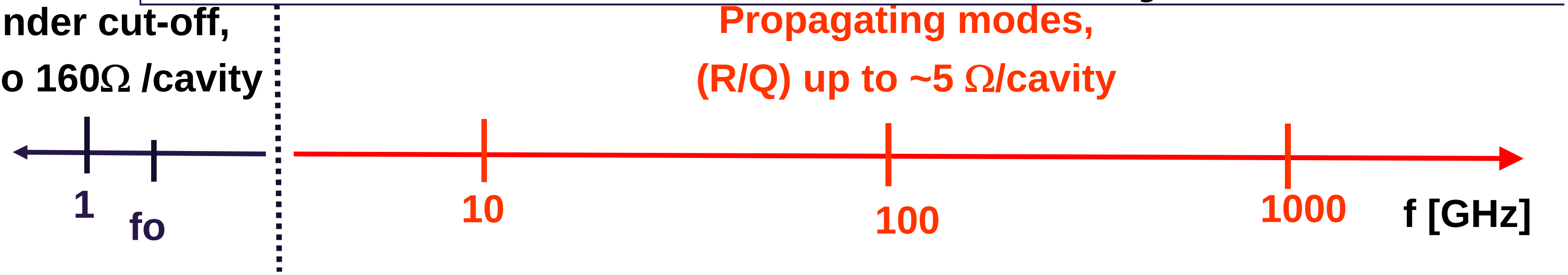


Snapshot of C:\SMARTEAMProd_Tmp\kosmicki\CAD000283202.CATProduct - 12/9/2009 15:51:41

European XFEL

Motivation

HOMs of the TESLA cavity:

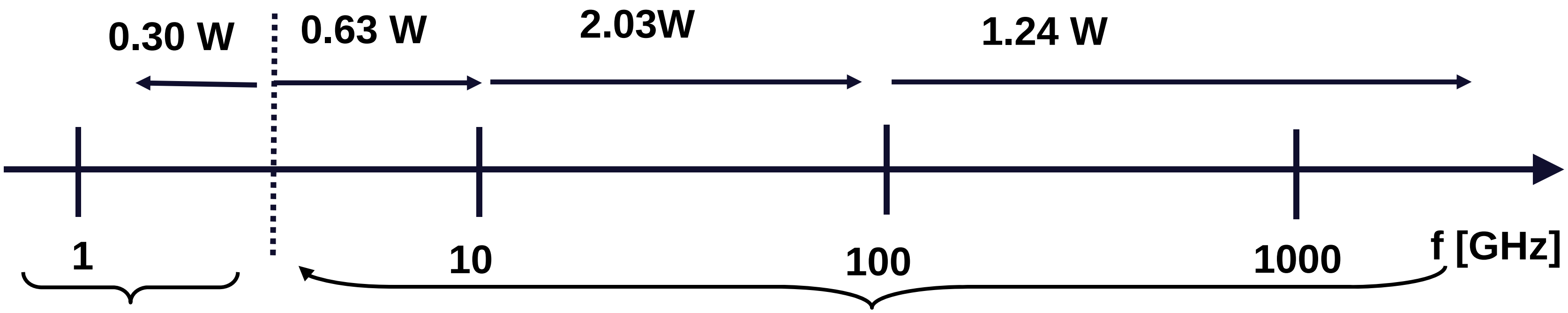


Modes under cut-off,
(R/Q) up to 160Ω /cavity

Propagating modes,
(R/Q) up to ~5 Ω/cavity

ILC beam (3.2nC & 3MHz & σ_z = 300 μm & 0.4% DF): 16.7 W/cryomodule

XFEL beam (1nC & 4.5 MHz & σ_z = 25 μm & 0.6% DF): 4.2 W/cryomodule



HOM couplers

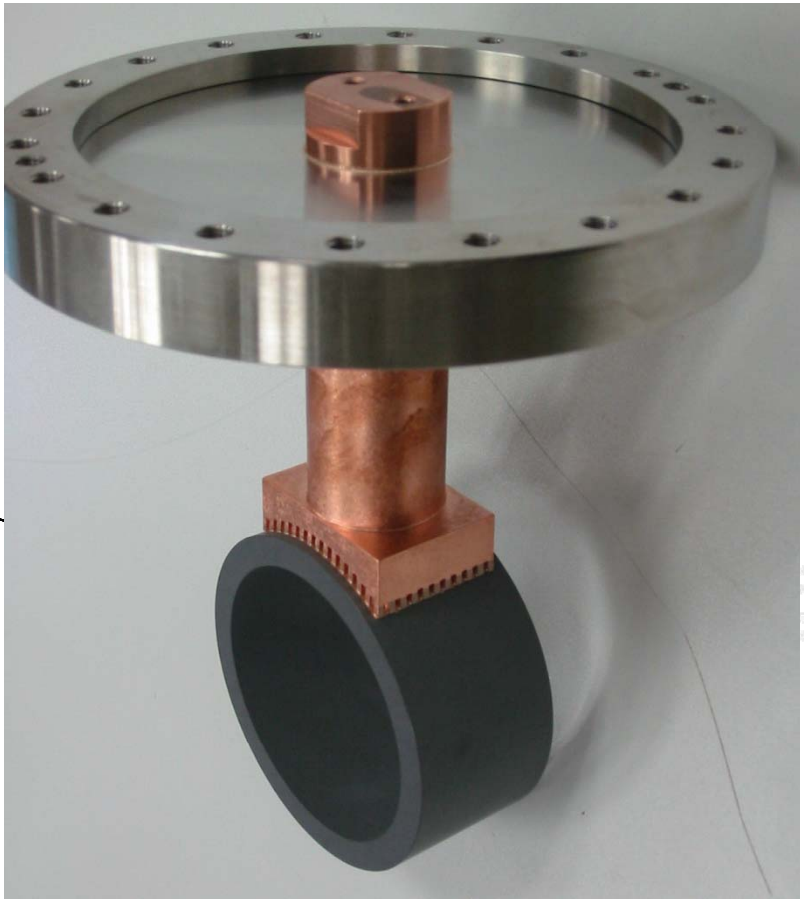
Beam Line Absorber

Beam Line Absorber

Mechanical design by Nils Mildner

Ceramic Ring: Ø 90mm
Length 50 mm
Thickness 10 mm

Lossy ceramic CA137 (Ceradyne):
ε´ =15 and ε´´ =4

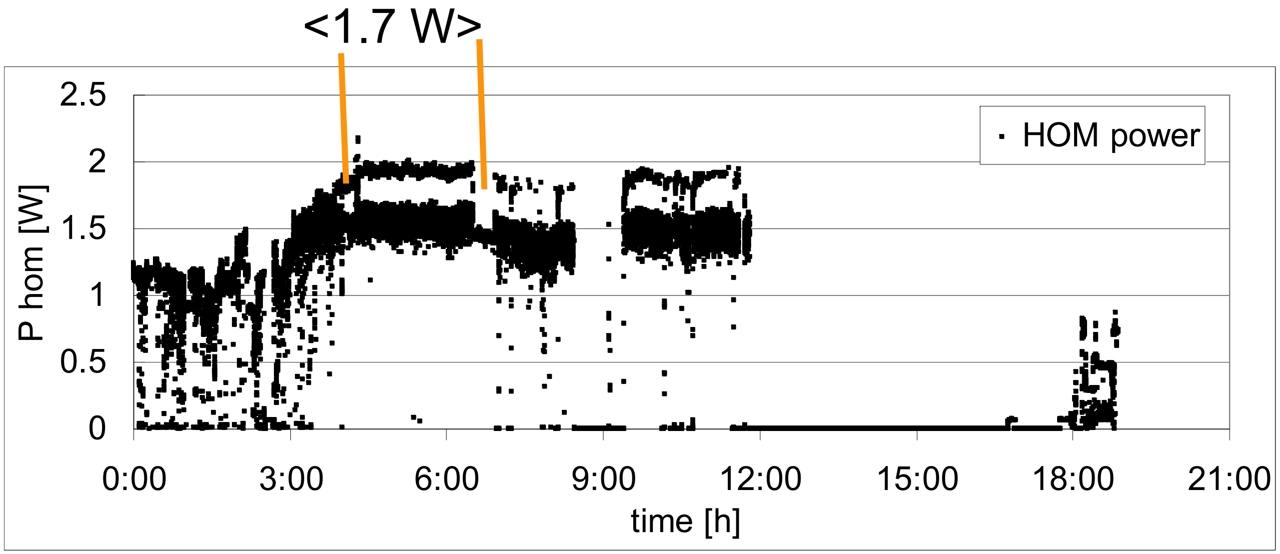


Estimated absorption efficiency for the periodic structure: one BLA/cryomodule is 83% (M. Dohlus)

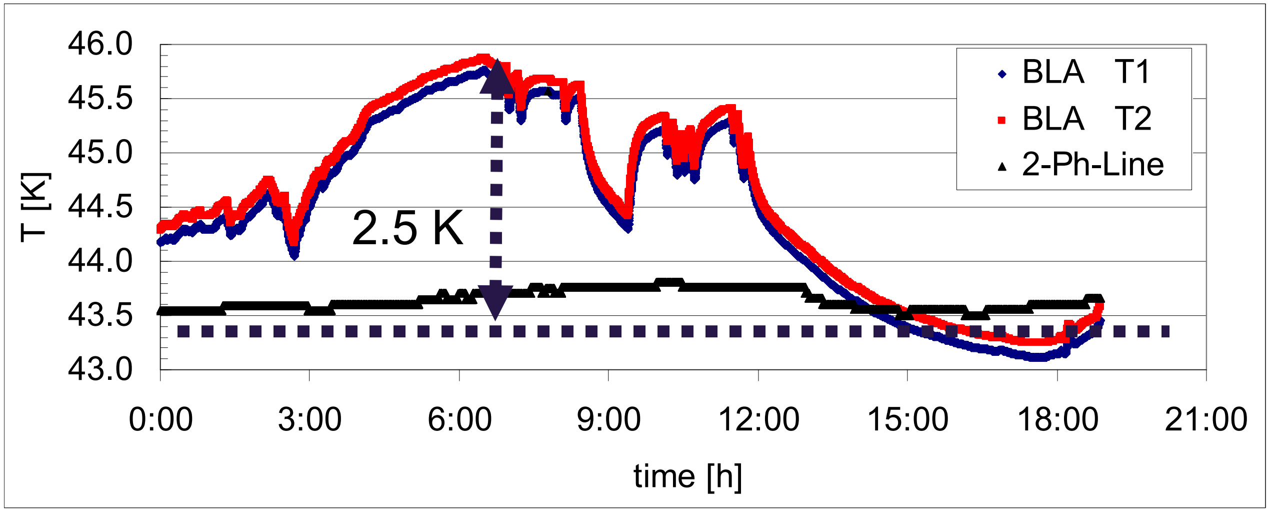
Tests in September 2008 and 2009

9 mA run in 2009

HOM Power in Cryomodule ACC6



Monitored BLA Temperature



Tests in September 2008 and 2009

Measured and calculated absorbed power in

Results of two tests at TTF-II

	September 08	September 09
Computed Absorbed Power [W]	0.180	0.255
Measured Absorbed Power [W]	0.143	0.325